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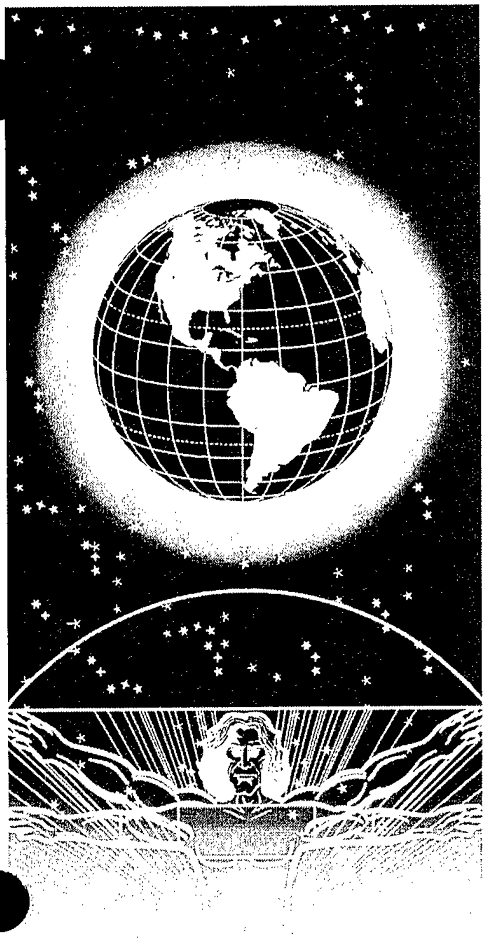

UNITED STATES AIR FORCE RESEARCH LABORATORY

ADAPTATION TO VISUAL TRACKING WITH A CENTRAL SIMULATED SCOTOMA

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RMiller

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14. ABSTRACT
Lasers on the battlefield could produce retinal injury that results in a blind spot (scotoma) in a person's central vision. The effect of a central 3 degree artificial scotoma on tracking and shooting with 3 different levels of target path difficulty and the effect of practice on the ability to track with a scotoma are reported. A three-degree artificial scotoma was produced using an SRI dual-Purkinje-image eyetracker. Subjects monocularly tracked a 6 minute of arc target with a joystick controlled cross hair. Eighteen subjects, 6 for each target path difficulty level, made 20, 1 minute tracking runs per day for 7 days. RMS error for the eye to target distance, cross hair to target distance, and the cross hair to target distance when shooting were determined. Eye position was monitored throughout the trial to determine tracking strategy. Three-degree scotomas decreased tracking and aiming performance dramatically for all three target path difficulty levels. The effect of a scotoma was greatest on the first trials when they were introduced and there was improvement with practice. All subjects learned to keep the scotoma away from the target and cross hair so that they would not be hidden by the scotoma. This strategy improved their performance. However, no subjects improved to their level of performance without a scotoma. These results further substantiate previous results indicating that scotomas may have significant impact on the completion of operational missions. Practice and exposure to a simulated scotoma may lessen but not eliminate the decrease in performance resulting from a central scotoma.

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ADAPTATION TO VISUAL TRACKING WITH A CENTRAL SIMULATED SCOTOMA

INTRODUCTION

For normal sighted persons, the fovea corresponds to the primary visual direction and the retino-motor center. Individuals with central scotomas develop an eccentric preferred retinal locus (PRL) for fixation, which they use much like the fovea.[1,2,3,4] Heinen and Skavenski[5] demonstrated that monkeys also quickly develop a new retinal locus inferior to the fovea after bilateral central foveal laser lesions. While the saccadic system adapted, saccadic adaptation occurred over a much longer period of time than the fixation system. Saccade trajectories gradually changed, bringing targets to intact retina rather than the lesioned fovea, but the adaptation was incomplete. Similarly, White and Bedell[4] found that in 21 patients with bilateral macular disease, while most had a PRF for fixation, only a third exhibited complete re-referencing of their eye movements to the preferred area. The eye movement control system does not seem to be treating the shift from fovea to PRL as equivalent to a shift of the real fovea. Whittaker, Cummings, and Swieson[6] concluded that while patients with macular scotoma use a PRL for fixation, the PRL does not acquire the characteristics of the foveal retino-motor center. The retino-motor null position did not move to the preferred retinal locus. They suggest that adaptation took place in a non-foveating mechanism.

Winterson and Steinman[7] have shown that perifoveal retina (6 degrees below the line of sight) can be used to track targets moving sinusoidally with smooth pursuit eye movements without practice. Therefore, foveal vision is not necessary for smooth pursuits following a target with this predictable path. They points out that his experiments indicate that the outlook for improvement in tracking ability after a foveal lesion is optimistic. Wyatt, Pola, Fortune, and Posner[8] report an ability to perform smooth pursuits with cues with a sudden onset of motion located eccentrically to the fovea.

Burbeck and Boman[9,10] have examined the effect of different size scotomas on a subject's ability to track targets and have shown that scotomas larger than 2 degrees significantly interfere with tracking ability. In contrast to this result, Callin et al.[11](1981) studied tracking in rhesus monkeys who were flashed with a white light calculated to bleach

a spot 0.7 mm on the central retina (equivalent to a scotoma between 2 and 3 degrees diameter) and the tracking was unaffected. The possible explanation given was that the monkeys used "off-center visualization" of the target to track. Some additional studies have been done at Letterman Army Institute of Research (LAIR)[12] on tracking ability with flashed lights or lasers used to produce glare and possibly a few seconds of flashbindness. Ability to track was significantly impaired. Eye movements were not recorded in these studies. Bertera[13] and Murphy and Foley-Fisher[14, 15, 16, 17, 18] created simulated central scotomas and found the scotomas interfered with the ability to do visual search tasks.

A central foveal scotoma generally impairs ability to perform dynamic visual tasks, even when the target is clearly visible with undamaged regions of retina. The decrement in performance with a foveal scotoma might be partially explained by the decrease in acuity and contrast sensitivity resulting from losing foveal vision, but an additional factor is the inability to develop a retino-motor center on an area of functioning retina away from the blind fovea. Failure to develop a new retino-motor center results in inappropriate and poorly controlled eye movements. When a central scotoma is present, foveating eye movements cause the scotoma to cover the target. Then the observer must make eye movements to bring the target to an unobscured retinal area. Best performance is expected only if the observer develops a complete re-referencing of eye movements to a PRL. Such re-referencing would result in maintenance of the target within a certain circumscribed area when tracking, and suppression of foveating saccades. White and Bedell[4] found evidence for a shift of the motor reference from the fovea in some patients with bilateral macular disease of years duration.

Lasers are increasingly a threat to aircrews in the military[1920], and a laser could potentially produce bilateral central scotomas in a pilot's vision. This experiment was designed to help determine the ability of a pilot with a central scotoma, compared to without a scotoma, to track and shoot a randomly moving target. The initial effects on tracking, eye movements, adaptations in eye movements and tracking strategy, and the development of a PRL were all examined. The subjects performed a dynamic tracking and shooting task with and without a central simulated scotoma. Three levels of tracking difficulty were evaluated to determine if difficulty level had an effect on the tracking strategy, ability, and adaptation. The results also provide insights into the eye movements and adaptation that might occur following the development of macular scotomas in clinical cases.

METHODS

Subjects

Eighteen subjects participated in the study (aged 21 - 43, average age 30.2 years, 3 female and 15 male). All of the subjects had minimum corrected vision of 20/20 and refractive error ranged from emmetropic (10 subjects) to -3.25 diopters myopic. The subjects were unpaid Air Force and contractor volunteers recruited from San Antonio Air Force bases. All of the subjects were naive as to the purpose of the experiment. Informed consent was obtained from each subject after the procedure was fully explained. Candidate subjects were given a trial with the eye tracker and were not accepted if there were any problems with the eye tracker maintaining lock on the eye, or tracking accurately over the target field. Four candidate subjects were rejected for difficulty with tracking.

Scotoma Generation and calibration

An SRI dual-Purkinje-image eye tracker (Fourward Technologies) with a visual stimulus deflector and scotoma device was used to record right eye position and to simulate a retinal scotoma. Detailed descriptions of this equipment are in the literature.[21, 22] To simulate a scotoma, a plane mirror was placed at the stabilization plane of a visual stimulus deflector. Rather than placing an obscuring spot directly on the mirror, as Crane and Steele described, an obscuring spot was placed on a thin glass plate which could be popped in front of the mirror by computer controlled solenoids. This allowed the scotoma to appear suddenly. The scotoma was stabilized on the retina by the eye tracker detecting eye position and driving two high-speed servo-controlled mirrors. The target on the monitor appeared to move normally. During experiments, each subject's head position was stabilized with a bite bar and a headrest to minimize eye movement artifacts originating from head movement. The subjects were instructed to minimize any head or body movement. The automatically moving autostage and the focus-servo were disabled for recordings because they caused artifacts that decreased tracking accuracy. The left eye was occluded.

To stabilize the scotoma, the observer turned dials to adjust the gain and offset of the electronics that drove the motor-driven mirrors so the scotoma followed eye movements precisely as fixation was directed to points about 5 degrees apart; left, right, up and down. The subjects then fixated points on a 5 x 5 grid to be confident that the scotoma was well stabilized. Subjects were relied upon for stabilization of the scotoma. They consistently reported good stabilization.

Following stabilization of the scotoma, calibration to determine eye position was completed. The subject fixated 5 positions, 2.1 degrees apart, along the central horizontal position, and 5 positions, 2.1 degrees apart, along the central vertical position. Two passes were made, so fixation was made on each point twice and a linear fit was made separately to the horizontal and vertical points. Eye position was linear to within a few percent over this area. If the R^2 value exceeded 0.950, the subjects then fixated points on a 5 x 5 grid (8.3 degree x 8.3 degree grid), and errors were determined for each point. If the average error did not exceed 0.25 degrees the calibration was considered adequate.

Procedures and Task

The subject tracked a target moving pseudorandomly in horizontal and vertical directions with a joystick-controlled reticle. The target motion was generated as a sum of sine waves so that the motion was unpredictable to the subject. The scotoma could be quickly introduced by a signal from the computer to a solenoid that suddenly moved the scotoma into position. A joystick (Flight Stick, CH Products) controlled the rate and direction of the reticle movement on the screen. To increase sensitivity, the joystick was modified, , to function as a voltage divider and the signal input was sent to an A/D converter. This was done to increase joystick sensitivity.

The target was a moving 6-minute of arc dot, 70 % contrast, on a monochrome monitor (Video Monitors, Inc., M2400 series). The brightness of the target, viewed through all of the optics of the stimulus deflector was 10 cd/m^2. The background was dark, so the borders of the stabilized scotoma could not be seen. Interestingly, if the scotoma slipped, a gray afterimage became visible at the location of the scotoma, and this was a cue to subjects that the scotoma stabilization and location needed to be adjusted.

The subject was instructed to track the moving dot target with a cross reticle and continually minimize the error of the cross from the target during each 1 minute tracking run. Each arm of the cross reticle was 0.5 degrees in length. In addition, the subject was instructed to take 10, self paced shoots at the target during each tracking run by pressing a trigger when he felt the cross and the target were aligned. When shots were taken, the computer softly beeped. They were not given any instruction or advice regarding tracking strategy, such as looking to the side of the target. At the end of the run, the subject was given feedback of the number of hits during the run on the monitor screen. A hit was recorded if the center of the cross was within 0.3 degrees of the target when the trigger was first depressed.

The voltage output of the tracker was fed to a 12 bit analog to digital converter (71 Hz) and eye position was recorded for later analysis. The reticle position for the duration of tracking and the position of the reticle when shooting were also recorded. The root mean squared (RMS) error was used to represent the overall efficiency of performance. The RMS error was calculated by taking the average of the squared position error values and then taking the square root. The aiming error was calculated from the reticle errors present when the button was pressed to shoot at the target. Poulton[23] discusses different error measures and recommends that RMS error be used as the measure of overall adequacy of tracking. RMS error for reticle position from the target was calculated on line at the conclusion of each run and reported to the subject as feedback.

In order to evaluate whether subjects were using a preferred area of retina when tracking the target with a scotoma, projected visual field was divided into 9 areas. A central circular area, designated area 9, corresponding to the location of the simulated scotoma, and 8 pie-shaped regions surrounding the central scotoma formed by 8 lines projecting from the center of the projected foveal location every 45 degrees. The first pie-shaped section to the right of the 12 o'clock position was labeled area 1, and the sections were labeled sequentially in a clockwise direction. This was done because the eccentric area used to track the target generally was scattered over a large portion of the visual field and could not be described accurately by a bivariant normal ellipse.

The location of the beginning and end points of saccades was also evaluated in order to determine the frequency of foveating saccades and whether subjects were using saccades to relocate the target on a preferred retinal locus. Eye movements were considered saccades if the velocity exceeded 30 deg/sec. Ditchburn[24] reported normal refixation saccades of 40 min of arc have velocities of 26 degrees/sec. The numbers and percentages of saccades for the starting position and ending position were determined for each of the 9 areas previously described in determining location and duration of dwell time.

The target path was composed of the sum of 3 horizontal sine waves combined with the sum of three vertical sine waves of the same frequencies. The phase of the sine waves was varied so that target path varied for each tracking run. The target never disappeared off the edge of the screen. The target position was limited to a central 12.5 degree square area of visual field. This wave form of a combination of 3 sine waves was chosen to make the target fairly unpredictable, in order to reduce the effects of human predictive capability.[25, 26] Also, sine waves were chosen because sine wave disturbances occur in flying.[23] In contrast to the

target movement for this experiment, for the LAIR studies,[12] the target moved horizontally at a constant velocity and was totally predictable. The subjects would be expected to track with reduced lag in these studies because of human predictive capability.

The difficulty of the tracking task was controlled by varying the frequencies of the sine waves making up the target path. By increasing the frequencies; the speed, number of reversals, and unpredictability of the target increased. The three levels of difficult had the frequencies listed in Table 1 below. For all target paths, the relative amplitude of each target path was inversely related to its frequency. This made the target paths less predictable because if the highest frequencies of a target path have a large amplitude, they tend to determine the average frequency of the reversals.[27] The velocity of the target was of course constantly changing since the target path was a sum of sinusoids. Table 1 also lists the average velocities (deg/sec), maximum velocities (deg/sec), and the approximate number of reversals for each target path difficulty level. Six subjects were assigned each level of difficulty. Each of the three female subjects was assigned to a different difficulty level.

Path	Frequencies (Cycles per minute)			Ave. Velocity	Max. Velocity	No. of reversals
A	6 2/3	4 4/9	2 2/3	1.4	2.6	10
B	16 2/3	11 1/9	6 2/3	3.6	6.7	21
C	26 2/3	17 7/9	10 2/3	5.7	10.6	40

TABLE 1. Sine wave frequencies comprising each of the target paths.

Schedule of runs

The subjects completed 140 tracking runs, 20 tracking runs per day, each of one-minute duration. The schedule for tracking is listed in Table 2. The first two days were done without a scotoma. The subjects became generally proficient during these two practice days, and baseline tracking without a scotoma did not generally improve in subsequent sessions. The subjects also practiced stabilizing the scotoma during these 2 days.

Tracking proficiency with a scotoma had leveled by days 6 and 7 and results on these two days with scotomas and without scotomas was compared. The twenty runs on each day were divided into two groups of 10 runs, half with a scotoma and half with out a scotoma. The scotoma/no scotoma runs within a block were given in random order. Block and day factors were considered in the ANOVA. For runs with a scotoma, the scotoma was inserted

5 seconds into the run. The first 5 seconds of tracking were not used in comparison of the scotoma and no scotoma conditions. The remaining 55 seconds were evaluated in 11 second groups.

The subject was allowed to take a break and get off the bite bar whenever he desired, though a general pattern was to take a break and get off the bite bar after every 5 tracking runs. The stabilization of the scotoma was checked and calibration was repeated after every 5 runs. If problems with tracking lock or stabilization were encountered, the run was repeated. This was a rare occurrence.

Three subjects were run per day, one for each target path difficulty level. The subjects were always tested at the same target path difficulty level. The subjects were tested at the same time each day.

Day 1, Thursday	**20 practice tracking runs without a scotoma.**
Day 2, Friday	**20 practice tracking runs without a scotoma.**
Day 3, Monday	**10 tracking runs without a scotoma followed by 10 with a scotoma.**
Day 4, Tuesday	**5 tracking runs without a scotoma followed by 15 with a scotoma.**
Day 5, Wednesday	**15 tracking runs with a scotoma followed by 5 without a scotoma.**
Day 6, Thursday	**A total of 10 tracking runs with a scotoma and 10 runs without a scotoma, random order.**
Day 7, Friday	**A total of 10 tracking runs with a scotoma and 10 runs without a scotoma, random order.**

TABLE 2. Subject Schedule

Data Summarization

From the digitized position data, the distance from the eye (d_e) to the target was calculated per the following formula:

$$d_e = \sqrt{(X_e - X_t)^2 + (Y_e - Y_t)^2}$$

Similarly, the distance from the crosshair to the target (d_c) was calculated:

$$d_c = \sqrt{(X_c - X_t)^2 + (Y_c - Y_t)^2}$$

(X_e, Y_e), (X_c, Y_c), and (X_t, Y_t) are, respectively, the coordinates for the eye, crosshair and the target. Only the data collected during the last 55 seconds of the run were used in the analyses so as to make the non-scotoma and scotoma trials of equal length.

For each run, the following quantities were computed:

1. Average of all eye to target distances.

$$\bar{d}_e = \frac{d_{e1} + d_{e2} + \ldots + d_{eN}}{N}$$

2. Variance of all eye to target distances.

$$d_e(Var) = \frac{(d_{e1} - \bar{d}_e)^2 + (d_{e2} - \bar{d}_e)^2 + \ldots + (d_{eN} - \bar{d}_e)^2}{N-1}$$

3. Root Mean Square (RMS) of all eye to target distances.

$$d_e(RMS) = \sqrt{\frac{d_{e1}^2 + d_{e2}^2 + \ldots + d_{eN}^2}{N}}$$

4. Average of all cross hair to target distances.

$$\bar{d}_c = \frac{d_{c1} + d_{c2} + \ldots + d_{cN}}{N}$$

5. Variance of all cross hair to target distances.

$$d_c(Var) = \frac{(d_{c1} - \bar{d}_c)^2 + (d_{c2} - \bar{d}_c)^2 + \ldots + (d_{cN} - \bar{d}_c)^2}{N-1}$$

6. Root Mean Square (RMS) of all cross hair to target distances.

$$d_c(Var) = \frac{(d_{c1} - \bar{d}_c)^2 + (d_{c2} - \bar{d}_c)^2 + \ldots + (d_{cN} - \bar{d}_c)^2}{N-1}$$

The above quantities were also computed for each run using the shooting data. A shot taken when the cross hair was within 0.3 degrees of the target center was called a hit. The ratio of hits to total shots was calculated for each trial. The subjects did not always take the full 10 shots, however it was generally 10 and rarely less than 8.

To study what happened within runs, the last 55 seconds of each run were divided into 5 groups of 11 seconds. The above quantities were calculated for each of the 11 second

groups. The data were analyzed using analysis of variance (ANOVA). The general form of the ANOVA for the overall trial and shooting data is listed in table 3.

Source of Variation	Degrees of Freedom
Path Difficulty (PD)	2
Subjects within PD (Su/PD)	15
Scotoma (S)	1
Scotoma x Path Difficulty	2
Scotoma x Su/PD	15
Day (D)	1
Day x Path Difficulty	2
Day x Su/PD	15
Day x Scotoma	1
Day x Scotoma x Path Difficulty	2
Day x Scotoma x Su/PD	15
Block (B)	1
Block x Path Difficulty	2
Block x Su/PD	15
Block x Scotoma	1
Block x Scotoma x Path Difficulty	2
Block x Day x Su/PD	15
Block x Day x Scotoma	1
Block x Day x Scotoma x Path Difficulty	2
Block x Day X Scotoma x Su/PD	15
Trials/D x B x S x Su	576
Total	719

TABLE 3. General form of the ANOVA for the overall trial and shooting data

When performing an ANOVA, assumptions are made that the treatment populations are normally distributed and that the variances are homogeneous. A common logarithm (Log10) transformation of error scores produced less skewed, more normal distributions of the data. Therefore, separate analyses were done on the data without and with the scotoma for both the original data and transformed Log10 data because heterogeneous variances are frequently converted to more nearly homogeneous variables by a log 10 transformation. The ratios of the error (variance) terms for the "with scotoma" condition, which consistently has the larger term, to the "without scotoma" condition were computed on the original data and the transformed log10 data. The ratios of the variances for the "without scotoma" condition compared to the "with scotoma" condition are much closer to one in every case. For example, the overall eye error from the target with the scotoma was 10,107 without a

scotoma and 129,515 with a scotoma, a ratio of 1:12.81. The log10 transformed overall eye error without a scotoma was 0.3643, and with a scotoma was 0.5028, a ratio of 1:1.38. Therefore, the variances are more nearly equal for the log10 transformed data than the original data and more nearly meet the condition of equal variances; and hence were used for the statistical analysis to interpret the data.

RESULTS

Tracking and Shooting without a scotoma

When tracking without a scotoma the subjects did a very good job of foveating the target. Their eyes generally stayed near the target. For the increasing levels of target path difficulty, the error was increased, but generally the subjects kept fixation very near the target. Figure 1, top panel shows an example of accurate tracking without a scotoma, distance from the target in degrees is plotted vs. time in seconds.

Cross hair position vs. time is shown in Figure 2, top panel, for the same tracking run and subject as in Figure l. The cross hair cannot move quite as quickly as the eye so the curve is more rounded. Most of the time the target is within 0.3 degrees (marked by the dotted line) of the target. The long vertical dashed lines indicate when the trigger was pressed to shoot at the target. The subject was able to take shots very accurately; the cross hair was very nearly aligned with the target. Note that this subject took 11 shots. Subjects were allowed to take more than 10 shots, but only the first 10 shots were used for evaluation. Accuracy decreased with increasing path difficulty. The hit/shot ratio was 0.97 for path difficulty level A, 0.66 for path difficulty B, and 0.29 for path difficulty C.

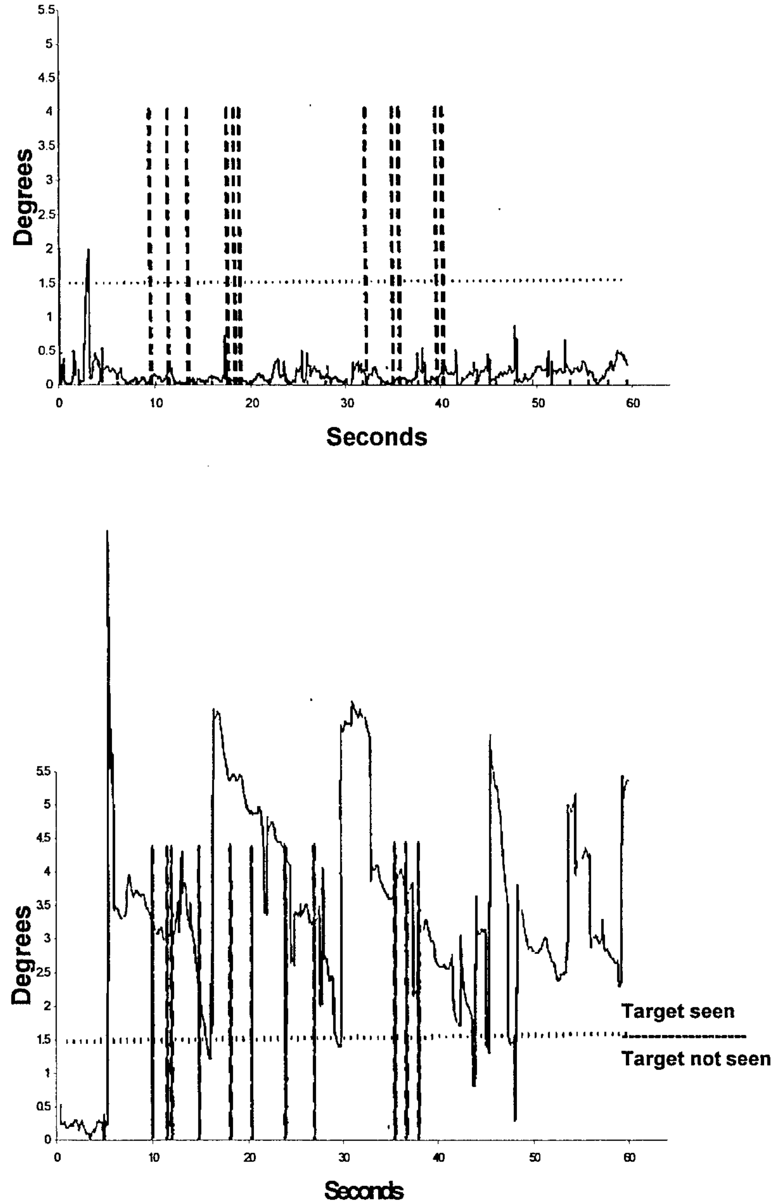

FIGURE 1.
Top panel: An example of eye tracking error (degrees) without a scotoma against time (seconds) for one run of a subject. The heavy dashed lines indicate when shots were taken. Shots were taken when the eye was tracking within a quarter degree of the target. The eye tracking error very rarely exceeded a quarter degree. Bottom panel: An example of eye tracking error (degrees) with a 3 degree scotoma against time (seconds) for one run of a subject after the subject had practiced and become accustomed to the task of tracking with a scotoma. The scotoma popped in after the first five seconds. Once again, the heavy dashed lines indicate when shots were taken. The subject offset his eye about 3 degrees from the edge of the scotoma. When the target disappeared in the scotoma, he would make about a large saccade to off set the target from the scotoma. The dashed line at 1.5 degrees represents the edge of the scotoma.

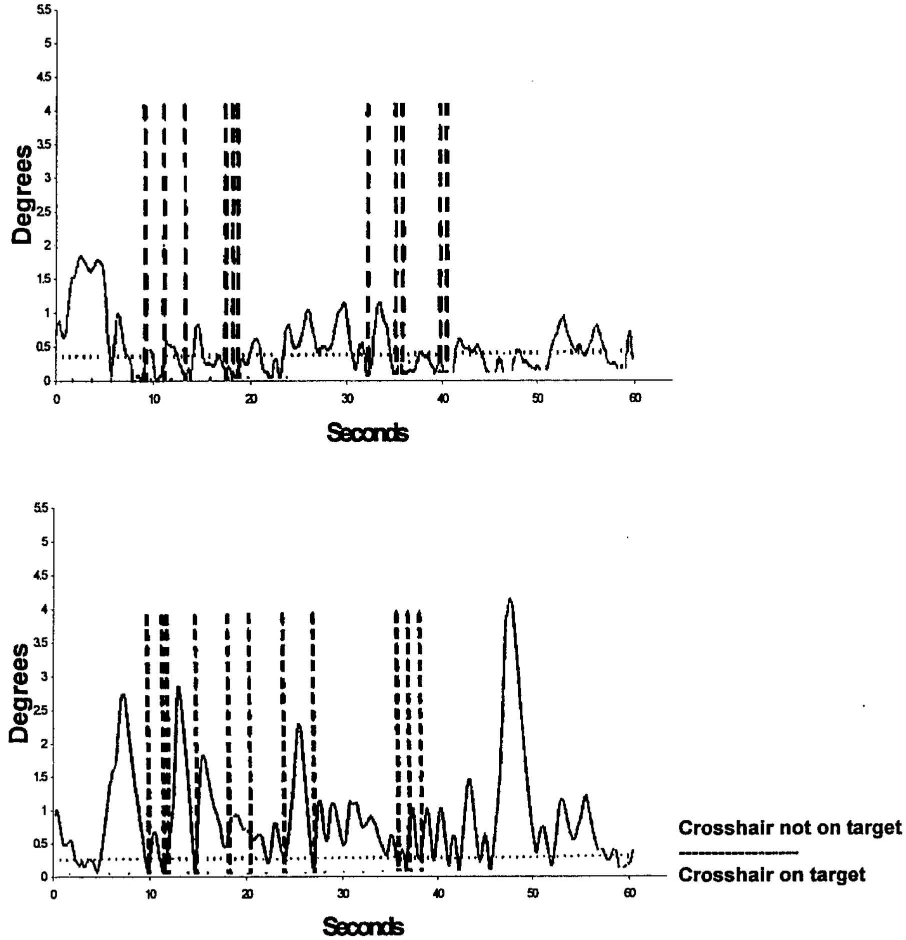

FIGURE 2.
Top panel: An example of crosshair tracking error (degrees) in contrast to eye position tracking error without a scotoma against time (seconds) for one run of a subject. The crosshair line is smoother with less sharp changes in direction. The crosshair position does not move as quickly or change direction as abruptly as the eye position does in figure 1. The heavy dashed lines indicate when shots were taken. Shots were taken when the cross hair was within 0.3 degrees of the target. The dashed line in the graph is at 0.3 degrees from the center of the target. Shots taken when the cursor was within this distance were counted as hits. Bottom panel: An example of crosshair tracking error (degrees) with a 3 degree scotoma against time (seconds) for one run of a subject after the subject had practiced and become accustomed to the task of tracking with a scotoma. The scotoma popped in after the first five seconds. Once again, the heavy dashed lines indicate when shots were taken. The dashed line is 0.3 degrees from the center of the target. Though the cross hair error was much larger in the top panel condition without a scotoma, the subject was fairly accurate in hitting the target.

Figure 3 shows an example of areas of dwell time. The projected foveal fixation point is in the center of this chart. The large circle marks the size of the 3 degree scotoma. The blocks are 25 min of arc on each side. The solid square indicates the target was within this area for 34% of the dwell time during a 1 minute tracking run. The open and filled squares together designate the visual field projected area the target occupied for 67% of the dwell time for the 1 min tracking run. Subject DM, was tracking a level A path difficulty target, the easiest. For higher levels of path difficulty, or poorer tracking, the target would be confined within several of these blocks around the central fixation point. For all path difficulty levels, including all subjects, the target was well maintained within the central 3 degrees of the visual field 93.3% of the time when tracking without a scotoma.

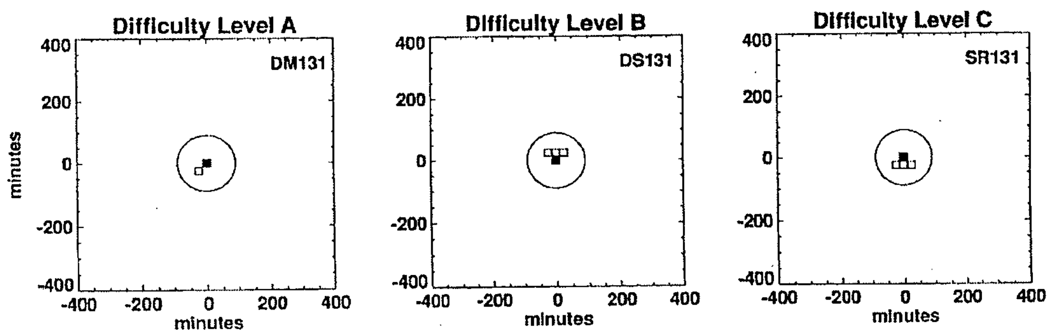

FIGURE 3.
Dwell time positions for the "no scotoma" condition for difficulty level A, level B, and level C. The solid squares include 34% of the dwell time and the open squares include 67% of the dwell time. The squares subtend 25 minutes of arc in the visual field on each side. Tracking was very accurate without a scotoma.

Initial runs with a scotoma

When first exposed to a scotoma during a tracking run, the target and cross hair would disappear because they would be covered by the scotoma. The cross hair or target would pop into view as they emerged from the scotoma and typically the subject would attempt to refixate the target on the fovea. When the target disappeared, the subject might also attempt to bring the target into view with a large saccade. For their first exposure to the scotoma, 10 of the 18 subjects spent over 50% of the viewing time with the target obscuring the target. The remaining 8 subjects shifted to eccentric retina to view the target, but were very inefficient and the target moved over large areas of the retina.

Figure 4 shows the eye tracking position relative to the center of the visual field corresponding to the fovea for the first exposure to a scotoma for 3 subjects, 1 subject for each difficulty level. The area of the scotoma is again marked with a circle. In all three of these examples the target was obscured by the scotoma for most of the tracking run. Some saccades were made which allowed eccentric retina to see the target, but saccades were also made toward the fovea that caused the target to be obscured.

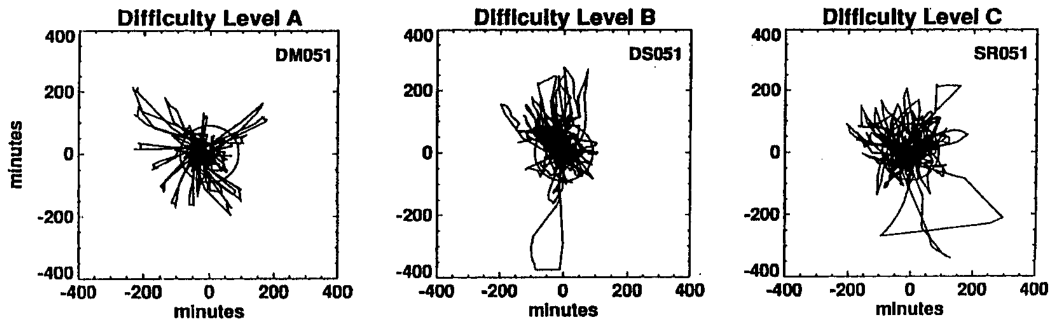

FIGURE 4.
Eye tracking position relative to the center of the visual field that corresponds to the fovea is shown for 3 different subjects for their first exposure to a scotoma for the 3 difficulty levels. The target was obscured by the central scotoma and the subjects made foveating saccades when the target appeared.

In comparing eye position, all the subjects, for the first exposure to the scotoma to eye position during the runs on day 6 and 7 after the subjects had experience with the scotoma, the mean eye position error was 2.2, degrees, as opposed to 3.3 degrees with the scotoma after practice. The subjects were obviously attempting to keep the scotoma away from the target. Without a scotoma the average eye position error was 0.85 degrees.

Changes with practice

All of the subjects, when questioned at the end of the experiment reported a strategy of attempting to keep the scotoma from obscuring the target and cross hair. Figure 1, lower panel, shows eye position vs. time after practice. The subject can see the target for the first 5 seconds and then the scotoma popped in the way of fixation. The subject made a large saccade to move the target to peripheral retina. He managed to keep the target in view for the entire tracking run except for 5 brief incursions that were corrected by saccades to put the target on peripheral retina. Foveating saccades were suppressed, though 3 saccades at 43, 45,

and 48 seconds into the run put the target into the scotoma where it was not visible. For this particular subject run, the pattern seems to be a large saccade to put the target out of the scotoma, and then the target drifted over time, toward the scotoma. This is apparent from 17-30 seconds and 30-44 seconds. When the scotoma encroached upon the target, a saccade was made away from the scotoma, and the target again with time appeared to drift closer to the target. This was a common pattern for many of the subjects.

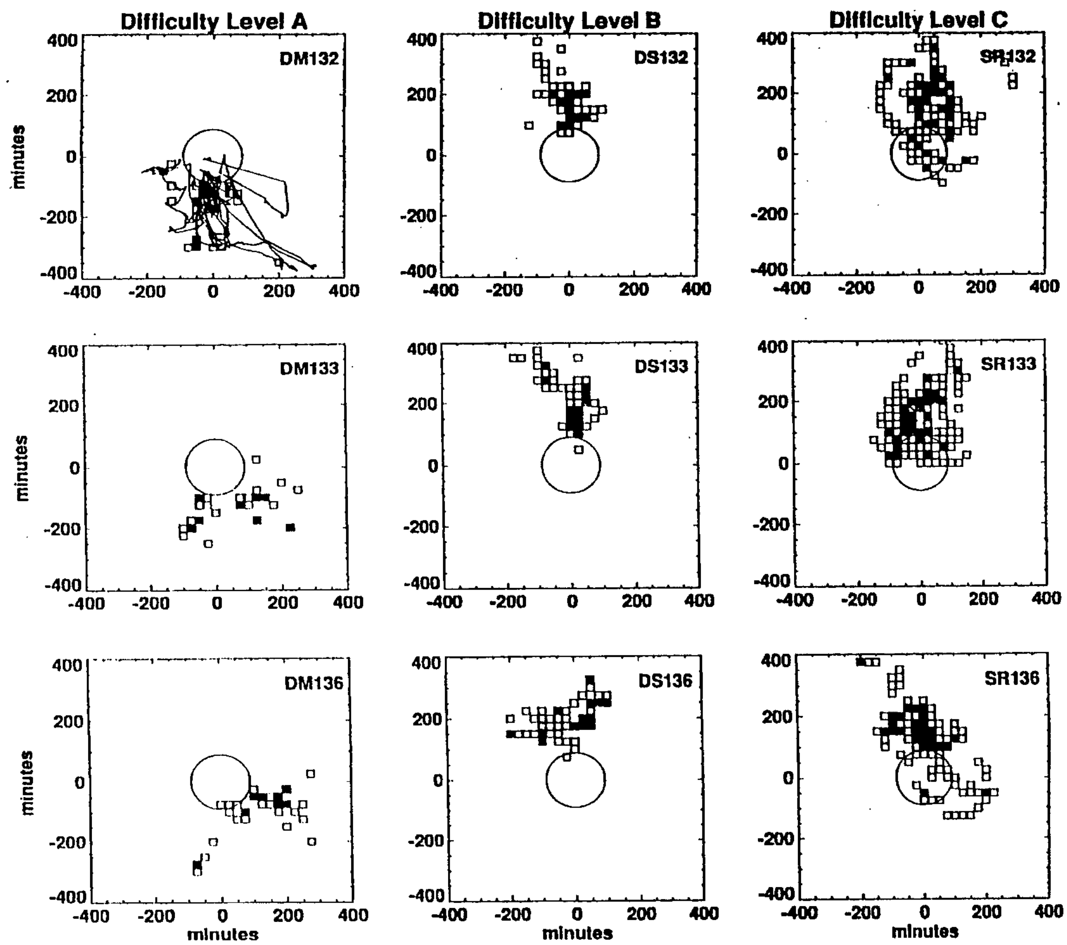

FIGURE 5.
Dwell time positions for the "scotoma" condition after practice by 3 subjects, each for 3 different tracking runs at their difficulty level for the experiment. Subjects did all their tracking runs at the same difficulty level. Subjects developed a strategy of using the same area of the retina repeatedly. The solid squares include 34% of the dwell time and the open squares include 67% of the dwell time. The squares subtend 25 minutes of arc in the visual field on each side.

Reports by Burbeck and Boman[9, 10] also contain some figures of eye position with time that demonstrate a similar pattern. Shots were taken when the target was approximately 3 degrees from the fovea rather than at the borderline of the scotoma where the best visual acuity would be expected. Because of the nature of the tracking task with an unpredictable moving target, the subjects may have used a less peripheral area of retina if they were fixating a stationary target rather than tracking a moving target. In fact, this was found to be the case when subjects performed a Snellen acuity task with the artificial scotoma.

Figure 5 demonstrates the repeated strategy of attempting to keep the scotoma from obscuring the target and cross hair by tracking the target with the same area of eccentric retina for repeated runs. The plot shows the visual field projection of the retina and the location of the scotoma relative to the target in the visual field. The tracking run for the simplist difficulty level is shown in the first column. The first plot in the upper left of the figure, shows a line connecting the digitized location of the target relative to fixation with the fovea and the scotoma. The squares represent areas of the retina corresponding the to dwell times corresponding to those areas of the retina when tracking. Similarly to Figure 3, the blocks are 25 min of arc on each side. The subject at difficulty level A consistently maintained the position of the scotoma above the target. This corresponded to tracking with superior retina. The subject for difficulty level B and the subject for difficulty level C both consistently place the scotoma below the target. This corresponded to tracking with inferior retina. For the higher difficulty level C, the quickness of the target makes it difficult for the subject to keep the target from entering the area of the scotoma. This was a common finding for the subjects at difficulty level C.

Data Summarization: "Scotoma" vs "no scotoma" condition after practice

One of the assumptions when performing an ANOVA is that the variances of the different treatment populations are homogeneous. Therefore, separate analyses were done on the data without and with the scotoma for both the original data and transformed log10 data. Heterogeneous variances are frequently converted to more nearly homogeneous variables by this log10 transformation. The error terms for both shooting and overall eye error, eye RMS, crosshair error, and crosshair RMS are much closer to one for the transformed log10 data than the original data. For example, the overall eye error from the target with the scotoma was 10,107 without a scotoma and 129,515 with a scotoma, a ratio of 1:12.81. The log10 transformed overall eye error without a scotoma was 0.3643, and with a scotoma was 0.5028, a ratio of 1:1.38. Therefore, the variances are more nearly equal for the log10 transformed

data than the original data and more nearly meet the condition of equal variances. For this reason, the plots in Figures 7, 8, and 9 are plotted for log10 transformed data, rather than the original data. Though the ratios are more nearly equal to one, there are there are still significant differences between the variances related to path difficulty and "scotoma" conditions.

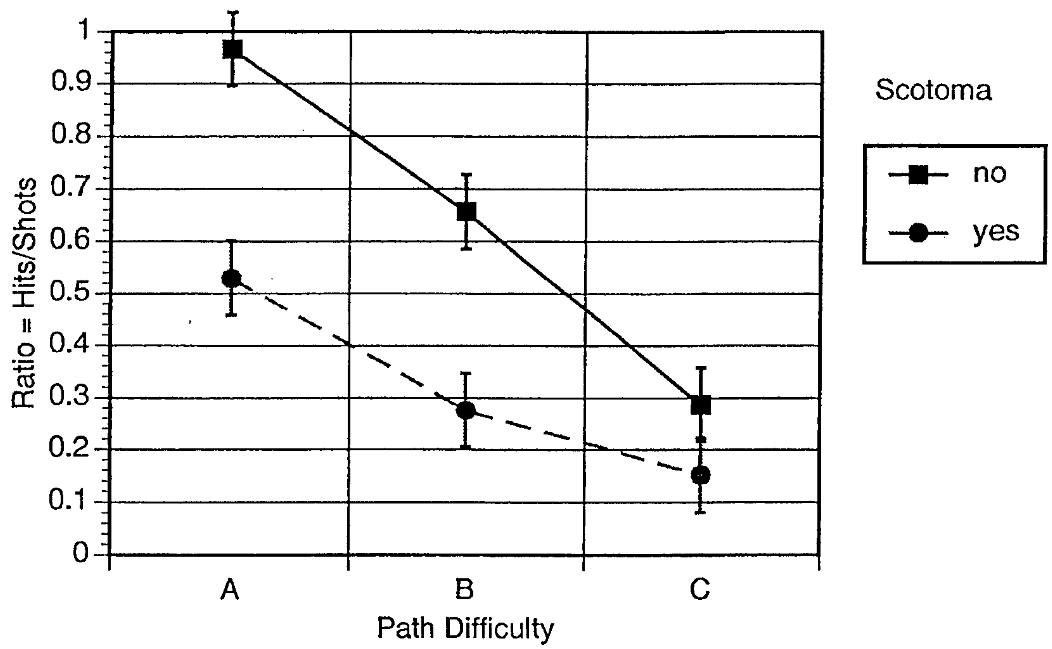

FIGURE 6.
Ratio of Hits/Shots for the 3 Path Difficulty levels. The ratio decreases as path difficulty level increases for both the "scotoma" and "no scotoma" conditions. The effect of the scotoma is greatest relative to the "no scotoma" condition for the easiest Path Difficulty (A).

A general form for the ANOVA for the overall trial and shooting data is listed in table 3. The appendix lists the path difficulty by scotoma means for all of the variables. Each variable will be briefly discussed separately. Significant effects and interactions ($p<0.05$) will be mentioned.

1. Ratio = Hits/Shots: The interaction is significant ($P=0.0009$) between scotoma condition and path difficulty. The fraction of hits is greater at all path difficulties: however, the differences (0.44, 0.38, and 0.14) vary significantly with path difficulty (Figure 6). As expected the fraction of hits decreases with increasing path difficulty, but the fraction of hits decreases more without the scotoma than with the scotoma.

Fractions like this ratio have a binomial distribution and generally a heterogeneous variance. For this reason, an arcsin transformation often makes the variance more homogeneous. An ANOVA was done using the arcsin transformation of the ratio. There were no important differences in the inferences between the analyses on the ratio and the analyses on the arcsin transformed data.

2. Mean Shooting Eye Error: The main effect for scotoma is significant (P=0.0001) with the average error for the scotoma being 5 times larger than that without a scotoma.

3. Log10 Shooting Eye Error: The main effect for scotoma is significant (P=0.0001). The Log10 shooting eye error with a scotoma is about 1.5 times larger than without a scotoma. There is a Block x Day x Path Difficulty (P=0.0459) interaction, and a Block x Scotoma x Path Difficulty interaction (P0.0445). There is not a significant main effect for block or day.

4. Log10 Shooting Eye Variance: This variable was analyzed to see if the size of the variance was affected by any of the factors in the experiment. Variances tend to have a skewed distribution. The log10 transformation makes the variances more normal (Gaussian), and hence the analyses of the variance are more valid.
If the size of the variance is "effected by factors in the experiment, this means that the variance is not homogeneous. As discussed above, a log10 transformation of the variables led to improved variance homogeneity. Even with this transformation, the main effects for scotoma and path difficulty are significant with P= 0.0001 and P=0.0333, respectively. The log10 variance is larger with a scotoma than without a scotoma, and the log10 variance increases with path increasing path difficulty. This result is not surprising.

5. Shooting Eye RMS: The results are essentially the same, but consistently slightly larger, as mean shooting eye error (#2). The main effect of scotoma is significant (P=0.0001).

6. Log10 Shooting Eye RMS: These results are essentially the same as log10 shooting eye error. There is a marginal Block x Day x Path Difficulty interaction (P=0.0681), and a Block x Subject x Path Difficulty interaction (P=0.0394).

7. Mean Shooting Crosshair Error: The main effects for Path Difficulty and Scotoma have P=0.0001. The error is larger with scotoma than without scotoma and the error increases as path difficulty increases.

8. Log10 Shooting Crosshair Error: The main effects of Scotoma (P=0.0001) and Path Difficulty (P=0.0001) are significant. The Scotoma x Path Difficulty interaction is significant (P0.0136). The log10 error is larger at all path difficulties; but the differences (0.38, 0.32, and 0.51) of with scotoma minus without scotoma decrease as the path difficulty increases. The error increases faster with a scotoma than without a scotoma.

9. Log10 Shooting Crosshair Variance: The main effects of Scotoma (P=0.0001) and Path Difficulty (P=0.0001) are significant, but the interaction is not significant (P=0.073). The variance is larger with a scotoma than without a scotoma and increases with increasing path difficulty.

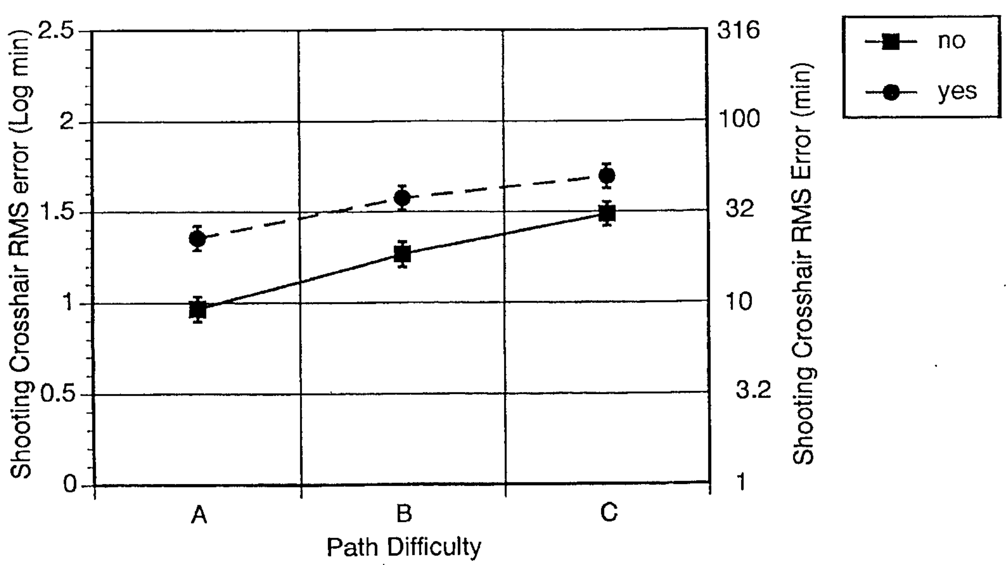

FIGURE 7.
Overall Shooting Crosshair RMS error (log min) on the left vertical axis and Overall Shooting Crosshair RMS error on the right vertical axis vs. Path Difficulty level. The effect of scotoma (yes) vs. no scotoma (no) is significant and is about 0.3 log units or twice as large for the "scotoma" condition compared to the "no scotoma" condition.

10. Shooting Crosshair RMS: The shooting error with a scotoma is about twice as large with a scotoma as without a scotoma. The results are essentially the same as mean shooting crosshair error. The main effects of Scotoma (P=0.0001) and Path Difficulty (P=0.0002) are significant.

11. Log10 Shooting Crosshair RMS: The results are essentially the same as log10 shooting crosshair error. The main effects of Scotoma (P=0.0001) and Path Difficulty (P=0.0001) are again significant. The Scotoma x Path Difficulty interaction is also significant (P=0.0242).

12. Mean Overall Eye Error: The Scotoma effect is significant (P=0.0001) and the mean with scotoma is about 5 times larger with a scotoma than without a scotoma. The errors are similar though slightly larger than the eye errors when shooting.

13. Log10 Overall Eye Error: The Scotoma x Path difficulty has marginal significance (p=0.0538). The means with scotoma, are essentially the same for all path difficulties, 2.27 log min. or 3 degrees, but without a scotoma the means increase with increasing path difficulty. The mean without a scotoma is 1.51 log min or about 0.5 degrees.

14. Log10 Overall Eye Variance: For the Scotoma x path difficulty mean square, P= 0.0287. The means increase with increasing path difficulty with and without a scotoma, however, once again they increase more without the scotoma than with it. The main effects of Scotoma (P=0.0001) and Path Difficulty (P=0.0001) are significant. Again, these significant effects indicate variance heterogeneity.

15. Overall Eye RMS: The test of Scotoma has P=0.0001. The mean with scotoma is about 5 times larger than the mean without scotoma.

16. Log10 Overall Eye RMS: The interaction of Scotoma x Path difficulty has P=0.0379. With the scotoma there are only small differences among the path difficulty means, but without the scotoma, the means increase with increasing path difficulty
(Figure 8).

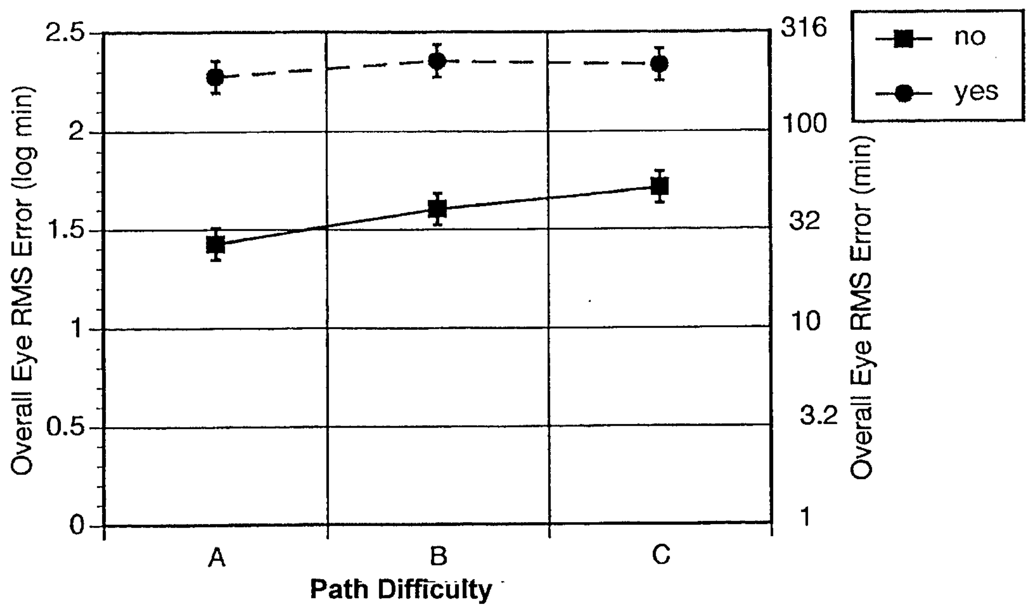

FIGURE 8.
Overall Eye RMS error (log min) on the left vertical axis and Overall Eye RMS error on the right vertical axis vs. Path Difficulty level. The effect of scotoma (yes) vs. no scotoma (no) is significant, but the there are only small differences with the Path Difficulty means when the scotoma was present. The scotoma was offset from the target by about 3 degrees (180 min) for all three path difficulty levels.

17. Mean Overall Crosshair Error: Both Scotoma and Path Difficulty have P=0.0001. The mean with scotoma is larger than the mean without scotoma. The path difficulty means increase with increasing difficulty.

18. Log10 Overall Crosshair Error: Scotoma x Path Difficulty has P=0.0053. Both with and without the scotoma, the means increase with increasing path difficulty, but the means increase more (steeper slope) without the scotoma than with the scotoma (Figure 8).

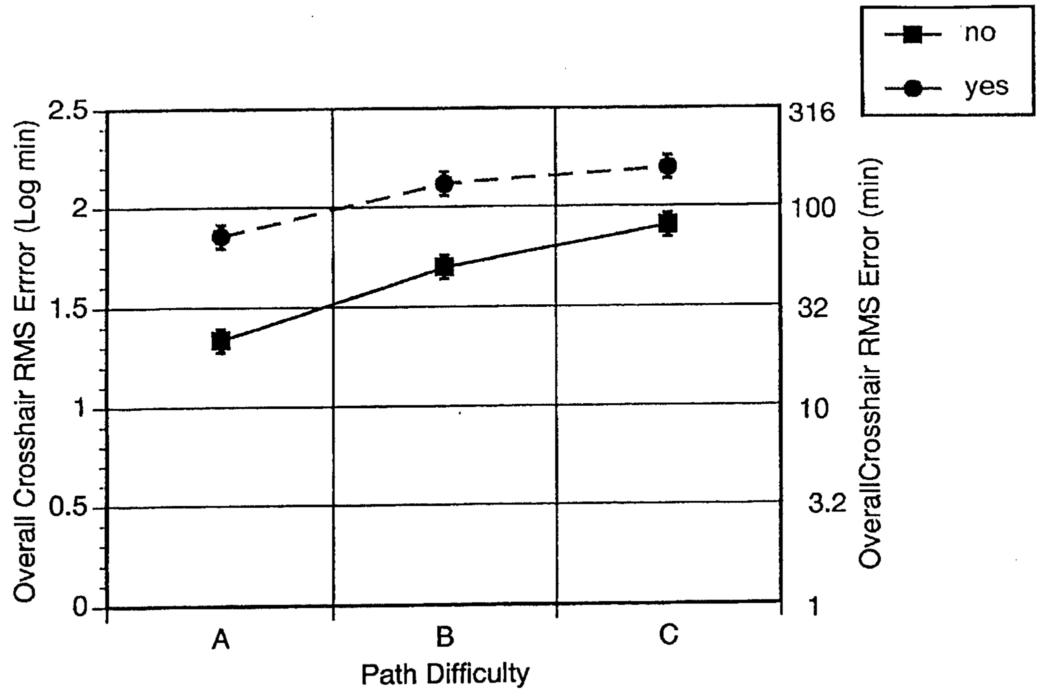

FIGURE 9.
Overall Crosshair RMS error (log min) on the left vertical axis and Overall Crosshair RMS error on the right vertical axis vs. Path Difficulty level. The RMS Crosshair error is greater with the scotoma than without a scotoma. The crosshair error increases with path difficulty. In contrast, the eye RMS error (figure 8) is about the same for each Path Difficulty level.

19. Log10 Overall Crosshair Variance: The variance is not homogeneous. There are effects for Scotoma (p=0.0001), Path Difficulty (p=0.0001), Scotoma x Path difficulty (p=0.0038), and Block x Scotoma (p=0.0367).

20. Overall Crosshair RMS: Scotoma (pO.OOOl), Path Difficulty (p=0.0001), and Block x Scotoma (p=0.0215) are significant. The results are essentially the same as mean overall crosshair error.

21. Log10 Overall Crosshair RMS: The results are essentially the same as log10 overall crosshair error.

"Error" variable vs. "RMS"variable

The "error" and the "RMS" are similar; the "error" is the arithmetic average of the distances, while the "RMS" is the square root of the average of the squared distance errors. RMS was always slightly larger than the "error." The ANOVA's generally showed the same

results, i.e. the same mean squares are generally significant (p=0.05) for the 2 analyses. In 5 out of the 8 comparisons between RMS and error values in the summarization of the "no scotoma" vs. "scotoma" condition on the last 2 days, the significant mean squares are the same (2 and 5, 7 and 10, 8 and 11, 12 and 15, and 18 and 21).

In those cases where the ANOVAS showed a mean squares to be significant for 1 and not the other of the paired analyses, the mean square which was not significant was only slightly larger than 0.05. For 3 and 6, the logl0 shooting eye error ANOVA has one more significant mean square (Block x Day x Path Difficulty, p= 0.0459) than the log10 shooting eye RMS (p=0.0681). For 13 and 16, the logl0 overall eye error ANOVA has one less significant mean square (Scotoma x Path Difficulty, p=0.0538) than the log10 overall eye RMS ANOVA (p=0.0379). For 17 and 20, the mean overall crosshair error ANOVA has one less significant mean square (Block x Scotoma, p= 0.0526) than the overall crosshair RMS (p=0.0215).

While RMS is generally used as the summarizing variable[23], the previous paragraphs explain that it makes little difference whether the "RMS" variable or the "error" variable is used to summarize the data. The differences between the two values were generally small.

Contribution of Block and Day variables

To determine if the block and day factors contributed significantly to the model, the mean square error for the model that included block and day (plus interactions).was compared with the mean square error for the model that did not include block and day (plus interactions) by an F test. The test was significant (P<0.005) for each variable. This indicates block and day factors (plus interactions) contribute significantly to the error.

Though statistically significant, the effects are not of practical significance. In Table 3, the main effects for Block and Day are never significant (P<0.05). The Day and Block means shows differences that are not consistently in the same direction. It is some of the interactions between Block, Day, Scotoma, and Path Difficulty that are significant. The interaction effects are not easily explained and do not appear to be of practical significance. The magnitudes of the differences between different blocks and between different days are generally about 1 min of arc or less. In addition, the standard deviations from the Mean Square Errors for the models without Block and Day compared to with Block and Day for the hit ratio and the log10 RMS variables show differences equal to less than 1 min of arc.

Analysis with Groups as a factor

The last 55 seconds were divided into 5 groups of 11 seconds. An ANOVA was again computed. Some data was missing due to a loss of tracker lock. This data was estimated. Log10 Eye RMS and log10 Crosshair RMS were primarily evaluated. The Log10 values were used because of an improvement in variance homogeneity with this transformation and because RMS is the usual variable for this type of data.

The number of shots falling within the 11-second groups varied considerably. In all but 3 of the 36 cases for group 5, the last 11 seconds, the average number of shots was less than 1. The 3 cases that averaged 1.0 or more shots in the last group were for the scotoma group. For group 4, 11 cases out of 36 were less than 1. In groups 1,2, and 3, there were respectively 30, 35, and 28 cases for which the average was greater than or equal to 2 shots.

For the log10 Eye RMS and log10 Crosshair RMS, the Group x Subject means, the Group x Path Difficulty means, and the Group x Path Difficulty x Scotoma means generally increase from group 1 to group 5. The Group x Scotoma interaction (P=0.0001) and Group x Path Difficulty (P=0.0116) interaction were both significant for Log10 Eye RMS. None of the other interactions were significant. The increases were of no practical significance. The largest increase from group 1 to group 5, the Log10 Eye RMS without a scotoma for Path Difficulty C amounted to only 1.05 min of arc (0.145 log units or 25.5%). The other increases were generally less than 1 min of arc.

Effect of blur on tracking and shooting

It can be argued that the main effect of decreasing ability to track and shoot with peripheral retina is not due to the blur of the target. Winterson and Steinman[28] (1978) point out that tracking is robust to degradation in luminance and therefore that spatial vision functions have little effect on pursuit. The same target can appear as a fuzzy achromatic mass or a sharply focused spot simply by changing its luminance. In agreement with these results, Burbeck and Boman[10] found that if target contrast for a spot target was above 3 times the threshold, the contrast of the target did not affect tracking ability. Haegerstrom-Portnoy and Brown[29] found that contrast did not affect smooth pursuit of unpredictable ramp targets when contrast was more than 0.3 log units (2 times) above contrast threshold.

While blurring of the spot target because of viewing eccentrically from the fovea might not have much of an effect on tracking ability, vernier and other hyperacuities might be expected to predict abilities for a tracking task. Because the eccentricity of viewing is

known, the expected ability might be predicted from the E2 values for hyperacuity. The E2 value for hyperacuity is generally between 0.4° and 0.9°[30]. Therefore, for an eccentric viewing angle of 3 degrees, the ability to track would be predicted to be 100 to 11.1 times worse than for foveal tracking. By this logic, an average error that is approximately twice as bad for both the shooting and overall crosshair error for the scotoma condition is surprisingly good. Using a typical E2 value for resolution for an eccentricity of1.5° to 4°, the expected ability using a region of retina 3 degrees from fixation is twice as bad as for foveal fixation. Inability to use a PRF as a visuo-motor center, and foveating eye movements would be expected to result in even worse performance.

When you consider that the log10 overall eye RMS error is approximately the same with a scotoma for all three path difficulty levels, and that the eye position error without a scotoma increases as path difficulty increases (Figure 8), then you might expect a similar pattern for the log10 overall crosshair RMS error (Figure 9). Error for the "with scotoma" condition would be expected to decrease with increasing path difficulty compared to the no scotoma condition. This is in fact the interaction ($p= 0.0046$) between path difficulty and scotoma condition that was found. The log10 eye RMS and the log10 crosshair RMS show a similar pattern.

Preferred retinal location for tracking

The subjects in this study did show a preferential area of the visual field for tracking the target. However, in contrast to previous studies[31, 32]comparisons between subjects did not demonstrate a preference for the use of superior or temporal retina to follow the target: individual subjects might use areas of retina to the right, left, up or down relative to the target. Whichever area of retina they chose, they tended to consistently stick with that area. For the conditions of this experiment, there were not any particular advantages to using any particular region or area of retina for tracking because the target moved unpredictably up and down and left and right,

A number of researchers[4, 31, 33] have found the pseudo-fovea with a central scotoma to be located on superior retina (inferior part of the visual field) or the right part of the retina (left part of the visual field). Interestingly, an explanation for using superior retina is that the lower part of the visual field is important for locomotion. Similarly, the argument for a systematic location on the left retina is the advantage when reading from left to right to see and plan the saccades for upcoming words. This systematic location of the PRF is found even though temporal regions of retina are generally found to be more sensitive[31] and have

significantly larger ERG amplitudes[34]. The argument can be made that since a specific area of the retina was not chosen for tracking the target, the visual tasks of the subject may have a influence on the determination of the location for a PRL.

There may be other factors at work in the development of a PRL for actual laser injury. Laser induced damage might produce a partial suppression and a selective low spatial frequency contrast sensitivity loss. Actual laser injury was found by Ness *et al.*[35] to produce a greater loss in the contrast sensitivity function than the loss with found with a similarly sized simulated scotoma. Oculo-motor as well as neural mechanisms may contribute to the development of a PRL.[36]

SUMMARY

A number of general conclusions can be made based on the results of this study. Tracking and shooting performance increase with practice. Tracking accuracy with the crosshair improved rapidly as the subjects learned to keep the target visible by using an area of retina that was not obscured by the scotoma. This strategy usually developed with less than 10 minutes of tracking runs. After practice, tracking and shooting performance is about twice as bad with a central 3 degree scotoma as without a scotoma. Subjects learned to use a preferred retinal locus to follow the target and learned to suppress foveating saccades. Increasing the task difficulty decreased tracking and shooting performance and made it more difficult for the subjects to track the target with a preferred retinal locus.

Potentially, lasers on the battlefield could produce retinal injury that would result in a scotoma in a pilot's central vision. The results of this investigation substantiate the view that lasres could have a significant impact on the completion of operational missions. Practice and exposure to a simulated scotoma might lessen, but not eliminate, the decrease in performance resulting from a central scotoma.

This investigation also has an application to understand the ability to function after any maculopathy; age related macular degeneration, macular dystrophies such as Stargardt's, retinal hole formation, solar retinopathy, commotio retinae, and toxoplasmosis that produce a central scotomas. Knowing a strategy to cope may be of benefit in teaching low vision patients to better cope with the loss of the fovea. Because subjects seemed to adapt readily to this task, and adopt an eccentric retina locus, this task might potentially have application to train patients to develop an eccentric retinal locus and suppress the inefficient, but natural tendency to foveate. One might also speculate that that this artificial scotoma technique

might be able to be used in strabismus with anomalous correspondence, or eccentric fixation to develop and train a foveation ability.

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APPENDIX A. MEANS (MINUTES OF ARC)

		Path difficulty			ALL PATHS
		A	B	C	
		MEAN	MEAN	MEAN	MEAN
1. Ratio Hit/Shot	Scotoma				
	No	0.97	0.66	0.29	0.64
	Yes	0.53	0.28	0.15	0.32
	Path Diff Mean	0.75	0.47	0.22	0.48
2. Mean Shooting Eye Error	Scotoma				
	No	23.83	31.38	43.81	33.01
	Yes	153.52	174.28	177.28	168.36
	Path Diff Mean	88.67	102.83	110.54	100.68
3. Log-IO Shooting Eye Error	Scotoma				
	No	1.31	1.44	1.56	1.44
	Yes	2.13	2.21	2.23	2.19
	Path Diff Mean	1.72	1.83	1.89	1.81
4. Log10 Shooting Eye Variance	Scotoma				
	No	1.94	2.22	2.52	2.23
	Yes	3.55	3.83	3.82	3.73
	Path Diff Mean	2.74	3.02	3.17	2.98
5. Shooting Eye RMS	Scotoma				
	No	25.80	33.84	47.40	35.68
	Yes	167.03	193.08	191.86	183.99
	Path Diff Mean	96.41	113.46	119.63	109.84
6. Log10 Shooting Eye RMS	Scotoma				
	No	1.35	1.47	1.60	1.47
	Yes	2.16	2.26	2.26	2.23
	Path Diff Mean	1.76	1.87	1.93	1.85
7. Mean Shooting Crosshair Error	Scotoma				
	No	8.48	16.85	28.59	17.97
	Yes	21.74	35.83	45.45	34.34
	Path Diff Mean	15.11	26.34	37.02	26.16
8. Log10 Shooting Crosshair Error	Scotoma				
	No	0.92	1.21	1.44	1.19
	Yes	1.30	1.52	1.64	1.49
	Path Diff Mean	1.11	1.36	1.54	1.34
9. Log10 Shooting Crosshair Variance	Scotoma				
	No	1.34	1.99	2.37	1.90
	Yes	2.18	2.64	2.87	2.57
	Path Diff Mean	1.76	2.31	2.62	2.23
10. Shooting Crosshair RMS	Scotoma				
	No	9.47	19.15	31.64	20.08
	Yes	24.78	41.29	52.45	39.51
	Path Diff Mean	17.13	30.22	42.04	29.80

11. Log 10 Shooting Crosshair RMS	Scotoma				
	No	0.96	1.26	1.49	1.24
	Yes	1.35	1.58	1.70	1.54
	Path Diff Mean	1.16	1.42	1.59	1.39
12. Mean Overall Eye Error	Scotoma				
	No	26.26	36.90	51.86	38.34
	Yes	187.13	207.99	197.88	197.67
	Path Diff Mean	106.69	122.44	124.87	118.00
13. Log 10 Overall Eye Error	Scotoma				
	No	1.37	1.52	1.65	1.51
	Yes	2.22	2.30	2.28	2.27
	Path Diff Mean	1.80	1.91	1.96	1.89
14. Log 10 Overall Eye Variance	Scotoma				
	No	2.27	2.72	2.92	2.64
	Yes	4.02	4.20	4.14	4.12
	Path Diff Mean	3.14	3.46	3.53	3.38
15. Overall Eye RMS	Scotoma				
	No	29.50	44.86	60.33	44.90
	Yes	212.28	238.53	225.46	225.42
	Path Diff Mean	120.89	141.70	142.89	135.16
16. Log 10 Overall Eye RMS	Scotoma				
	No	1.43	1.61	1.72	1.58
	Yes	2.28	2.36	2.34	2.33
	Path Diff Mean	1.85	1.98	2.03	1.95
17. Mean Overall Crosshair Error	Scotoma				
	No	18.94	43.35	69.62	43.97
	Yes	58.93	105.37	130.12	98.14
	Path Diff Mean	38.93	74.36	99.87	71.06
18. Log 10 Overall Crosshair Error	Scotoma	1.27	1.62	1.83	1.57
	No				
	Yes	1.74	2.00	2.10	1.95
	Path Diff Mean	1.50	1.81	1.97	1.76
19. Log 10 Overall Crosshair Variance	Scotoma				
	No	2.21	2.97	3.40	2.86
	Yes	3.41	3.93	4.05	3.80
	Path Diff Mean	2.81	3.45	3.73	3.33
20. Overall Crosshair RMS	Scotoma				
	No	22.48	52.58	83.92	52.99
	Yes	76.83	136.40	161.94	125.06
	Path Diff Mean	49.65	94.49	122.93	89.03
21. Log10 Overall Crosshair RMS	Scotoma				
	No	1.34	1.70	1.91	1.65
	Yes	1.85	2.11	2.20	2.05
	Path Diff Mean	1.59	1.90	2.05	1.85

APPENDIX B. "P" VALUES

	Mean Square	P
1. Ratio Hit/Shot	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0009
	BxPD	0.0357
2. Mean Shooting Eye Error	Scotoma	0.0001
3. Log10 Shooting Eye Error	Scotoma	0.0001
	BxDxPD	0.0459
	BxSxPD	0.0445
4. Log10 Shooting Eye Variance	Path Difficulty	0.0333
	Scotoma	0.0001
	BxS	0.0006
5. Shooting Eye RMS	Scotoma	0.0001
6. Log10 Shooting Eye RMS	Scotoma	0.0001
	BxSxPD	0.0394
7. Mean Shooting Crosshair Error	Path Difficulty	0.0001
	Scotoma	0.0001
8. Log10 Shooting Crosshair Error	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0136
9. Log10 Shooting Crosshair Variance	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0728
10. Shooting Crosshair RMS	Path Difficulty	0.0002
	Scotoma	0.0001
11. Log10 Shooting Crosshair RMS	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0242
12. Mean Overall Eye Error	Scotoma	0.0001
13. Log10 Overall Eye Error	Scotoma	0.0001
14. Log10 Overall Eye Variance	Path Difficulty	0.0263
	Scotoma	0.0001
	DxS	0.0028
	BxS	0.0030
15. Overall Eye RMS	Scotoma	0.0001
16. Log10 Overall Eye RMS	Scotoma	0.0001
	SxPD	0.0379
17. Mean Overall Crosshair Error	Path Difficulty	0.0001
	Scotoma	0.0001
18. Log10 Overall Crosshair Error	Path Difficulty	0.0001
	Scotoma	0.0001
	BxS	0.0426
19. Log10 Overall Crosshair Variance	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0038
	BxS	0.0367
20. Overall Crosshair RMS	Path Difficulty	0.0001
	Scotoma	0.0001

	BxS	0.0215
21. Log10 Overall Crosshair RMS	Path Difficulty	0.0001
	Scotoma	0.0001
	SxPD	0.0046
	BxS	0.0299